PROPERTY OF
PRINCETON UNIVERSITY LIBRARY
RECEIVED APR 22 1939

The PSYCHOLOGICAL RECORD . . . .

APRIL, 1939
Vol. III No. 6

THE RELATION BETWEEN INTENSITY AND HARMONIC STRUCTURE IN VOICE

ORVILLE J. BORCHERS, PH. D.

THE PRINCIPIA PRESS, INC.
BLOOMINGTON, INDIANA

Price of this number, 25 cents

EDITOR — J. R. KANTOR, *Indiana University*
BUSINESS EDITOR — C. M. LOUTTIT, *Indiana University*

DEPARTMENTAL EDITORS:

ABNORMAL — EDMUND S. CONKLIN, *Indiana University*
CHILD — HELEN KOCH, *University of Chicago*
CLINICAL — B. M. CASTNER, *Yale University*
COMPARATIVE — E. A. CULLER, *University of Rochester*
EDUCATIONAL — J. G. PEATMAN, *City College of New York*
EXPERIMENTAL — B. F. SKINNER, *University of Minnesota*
MEDICAL — NORMAN CAMERON, M. D., *Cornell Medical College*
PHYSIOLOGICAL — C. F. SCOFIELD, *University of Buffalo*
PSYCHOMETRICS — J. P. GUILFORD, *University of Nebraska*
SOCIAL — NORMAN C. MEIER, *University of Iowa*
ASSISTANT EDITOR — J. W. CARTER, JR., *Indiana University*

The Principia Press, Inc., has undertaken the publication of this co-operative journal to afford authors the opportunity of immediate publication at the least possible expense. The present low cost of publication, and possible future reductions, depend entirely upon the number of subscriptions. The subscription price has been made low to induce individuals to subscribe. Under the Articles of Incorporation of the Principia Press no profit can be made on any of its publications. Therefore an increase in the number of subscribers will be reflected in reduced costs to authors and in increase in the number of pages published annually.

EDITORIAL BOARD. The above named board of associate editors have agreed to serve in an active capacity for a period of three years, and all manuscripts will be submitted to them.

MANUSCRIPTS may be sent to the appropriate associate editor or to Dr. J. R. Kantor. Longer papers (30 or more typewritten pages) in the above mentioned fields are especially desired.

COSTS. The cost of publication will be $2.00 per page of approximately 470 words. The charge for line cut illustrations will be $2.00 regardless of size. Special charges will have to be made for complex tabular matter and for half-tone or colored illustrations.

REPRINTS. One hundred copies of each paper will be supplied gratis. Additional copies may be purchased in any quantity at a rate which will be set when the author is informed of the cost of publication.

ROYALTIES. Fifty per cent of the net income from the sale of individual copies, or from copies sold as part of back volumes, will be credited as royalties to the author's account. Royalties cannot be paid on income from subscriptions current in the year of publication.

SUBSCRIPTIONS. The subscription price is $4.00 per year for an annual volume of approximately 500 pages. Individual papers will be sold at an advertised price, which will depend upon the size of the article. Foreign subscriptions will be $4.50.

CORRESPONDENCE concerning editorial matters should be addressed to Dr. J. R. Kantor, Indiana University. Business correspondence should be addressed to Dr. C. M. Louttit, Principia Press, Inc., Bloomington, Ind.

THE RELATION BETWEEN INTENSITY AND HARMONIC STRUCTURE IN VOICE*

By Orville J. Borchers, Ph. D.

I. Problem and Procedure

Previous studies in quality. The purpose of this investigation was to determine the changes in harmonic structure with changes in the intensity level at which a specified vowel was sung. Three intensity levels corresponding to pp, mf, and ff, and the vowel *a* as in father, were taken as the basis of this study.

As far as is known, no work has previously been reported showing the effect of intensity upon the harmonic structure of the sung tone.[1] A number of studies (4, 5, 10) showing the effect of varying intensities upon the harmonic structure of tones produced by stringed and wind instruments have been reported.

Subjects. The subjects used in this investigation were the best male artists available. CT and OB were basses and HS and AK were tenors, the latter a distinguished American tenor.

The recording set-up. The apparatus consisted chiefly of a crystal microphone, an oscillograph, an amplifying system, and a power level indicator which was connected to an amplifier in parallel with the oscillograph amplifier. The response of this amplifier was approximately flat from 100 to 3,000 cycles. The power level indicator was calibrated in decibels and gave the approximate values of the differences in the intensity levels of the various tones.

Procedure. Great care was taken to keep all the variables except intensity as constant as possible. The *S* was asked to assume an indicated position and a direction toward the microphone which

*Recommended for publication by Dr. B. F. Skinner, February 8, 1939.

[1]Laase (6) and Talley (7) have shown the effect of pitch and intensity on the harmonic structure of vowels in spoken sounds. Their findings for the vowel *a* as in *father* is in general accord with the conclusions of this study.

were constant from tone to tone. The instruction to sing the pure vowel *a* was definitely stressed. The pianissimo tones were sung as softly and the forte tones as loudly as possible within the limits of artistic performance and the mezzo tones were sung approximately midway between the pianissimo and forte intensities, at three pitch levels corresponding to the upper, medium, and lower parts of each singer's singing range.[2]

An assistant recorded the relative intensity as given by the power level indicator at the moment the record was taken. These values are only close approximations (within two or three db) to the exact intensity differences, inasmuch as minor intensity fluctuations make an accurate reading difficult.

In each instance an oscillogram of sufficient length to include a pitch vibrato cycle and of sufficient speed to make it available for harmonic analysis was obtained. Following a previous study in which it was pointed out that large changes occur in various partials during the pitch vibrato, it was deemed necessary to select four waves representing the crest, trough, and two nodal points in order to get a fair statement of the harmonic structure. Consequently, four waves from each of the nine tones produced by each singer, 144 waves, were analyzed by means of an Henrici analyzer. Proper corrections for oscillograph loss were made and the corrected values reduced to a percentage basis. The mean percentage value for each partial during a pitch vibrato cycle was obtained.

II. Discussion of Results

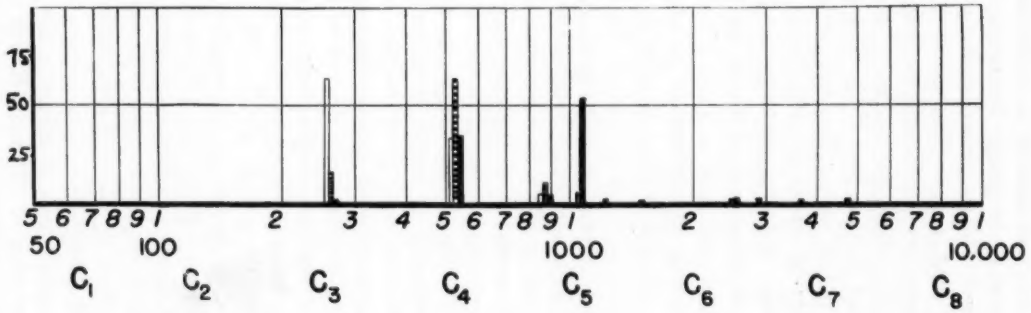
Fig. 1 shows the acoustic spectra of three tones of the same singer and vowel, sung at the three different intensity levels at approximately the same frequency.[3] The first important difference

[2]The character of the vowel at the extreme intensities may be questioned. However, each singer insisted that he was singing a normal vowel at all intensity ranges. It is probable that the vowel formant is changed considerably in tones produced by artists at extreme intensities.

[3]The inconsistency with which singers maintain a given pitch is well known. Aside from the vibrato, there is present the tendency to reproduce a given pitch a few vibrations sharp or flat. The small differences of one or two vibrations in fundamental frequency in the tones here studied, however, do not materially affect the conclusions.

FIGURE 1

Percent of Total Energy.



Acoustic spectra representing harmonic analyses of three comparison tones sung by OB. Pp, mf, and ff tones indicated by the unshaded, semi-shaded, and shaded ordinates respectively. The mf and ff tones were sung 12 and 26 db respectively above the pp tone.

in the timbre of the three tones is the smaller proportion of energy in the fundamental at the greater intensities. The fundamentals of the pp, mf, and ff tones contain, respectively, 61, 18.6 and 1 per cent of the total energy. The second important difference is that the maximum energy is found in the first, second, and fourth partials, respectively, of the pp, mf, and ff tones. These partials contain 61, 63 and 52.9 per cent of the total energy, respectively, of the pp, mf, and ff tones. The third important difference is the greater distribution of energy extending to more of the higher partials in the tones of greater intensity.

The number of db increase of the mf and ff tones above the pp tone is shown for each singer in Table I. Tables II—V inclusive indicate comparatively the differences in harmonic structure in each of the pp, mf, and ff tones sung by each of the four subjects.

A decrease in the amount of energy in the fundamental with an increase in intensity is consistently marked. In each case, there is a smaller percentage of energy in the fundamental of the mf tone than in the fundamental of the pp tone sung at the same pitch, and a smaller percentage of energy in the fundamental of the ff tone than in that of the mf tone sung at the same pitch. There is an increasing percentage of energy in the fundamental from low to high tones which are sung pp in the cases of OB and AK, the highest pp tones showing the greatest proportion of energy (61 and 71 per cent, respectively). In the case of CT there is a slight but not consistent increase in the percentage of energy in the fundamental of the pp tones on the higher pitches, while HS shows the reverse. Similarly, the records of CT, OB, and AK show consistent increases in the percentage of energy in the fundamental of mf tones from low to high pitches. HS shows only a small inconsistent change. OB and HS show a consistent decrease in the percentage of energy in the fundamental of ff tones from low to high pitches. The records of CT and AK, however, do not show a similar consistent change.

The greatest percentages of energy in the fundamental occur in the highest pp tones of OB and AK with 61 and 71 per cent, respectively. The smallest percentages of energy on the fundamental occur in the ff low G_1 of CT and in the ff high tones of HS and OB, with less than 1 per cent of the total energy. It is

reasonable to conclude that the fundamental possesses the greatest percentage of energy in the high pp tones and the smallest in the ff tones.

The second partial is considered separately because it shows characteristic changes very similar to the fundamental. Tables II—V inclusive indicate a consistent decrease in the energy of this partial with an increase in intensity except in the high tones of OB and AK. The second partial tends to increase in energy on the higher tones, particularly those of pp or mf intensity, the highest percentages occurring in the high pp tones of CT and HS. Minimal percentages of energy in the second partial occur on the lower ff tones.

It is evident from Tables II—V inclusive that the energy in ff tones is spread over a greater number of partials than in the mf or pp tones. Any partial showing as much as .25 per cent of the total energy in any one of the four selected waves during the pitch vibrato cycle is included in the averages in the Tables. Upon this basis, the energy in tones of different intensities regardless of pitch is spread on an average in the following number of partials:

pp tones	6.1 partials
mf tones	8.7 partials
ff tones	10.9 partials

There are the same number of tones and an equal distribution of high, medium, and low tones in each of the three above groups. The energy in the forte tones is spread over nearly twice as many partials as in the pianissimo tones.

The centroids of energy of the tones of greater intensity fall consistently at higher frequencies than in tones of less intensity.[4] The largest increase in the frequency of the centroid from pp to ff is 1190 cycles. The smallest increase is 161 cycles. Examination of Tables II—V inclusive will show that the increase in the frequency of the centroid with increase in the intensity level is the result of four causes: (a) There is less energy in the first and second partials at greater intensity levels. (b) There is a greater spread of energy

[4]The centroid of energy is the statistical mean of the dispersion of the energy under consideration. It is indicated by a frequency which represents the mean point of the dispersion. Fifty per cent of the energy falls below this mean and 50 per cent above it.

to successively higher partials with the appearance of energy in higher resonance regions, particularly around 2,500 cycles in tones sung at greater intensity levels. (c) The energy in the strong lower formant region for the vowel *a* around 600 cycles frequently decreases with an increase at higher frequencies in tones sung at greater intensity levels. (d) A greater percentage of energy frequently falls in the higher formant region (between 900 and 1,200 cycles) for the vowel *a* in tones sung at greater intensity levels.

III. Summary

The following conclusions are based upon the analysis of the tones produced by the four artists used in this investigation and for the vowel *a* only:

(1) There is without exception a greater percentage of energy in the fundamental of tones sung with less intensity but at the same approximate pitch. Inversely, there is less energy in the fundamental of tones sung at greater intensity levels but at the same approximate pitch.

(2) There is an increasing amount of energy in the fundamental from low to high tones which are sung pianissimo.

(3) The second partial shows characteristic changes in energy with changes in intensity level which are very similar to the changes in the fundamental.

(4) The centroid of the total dispersion of energy changes to markedly higher frequencies in tones sung at greater intensity levels but at the same pitch.

TABLE I

INCREASE IN INTENSITY LEVELS OF TONES SUNG MF AND FF IN DB ABOVE THE INTENSITY LEVEL OF TONES SUNG PP

Intensity level	Singer CT Pitch			Singer AK Pitch			Singer OB Pitch			Singer HS Pitch		
	G_1	C_2	G_2	G_2	C_3	G_3	C_2	G_2	C_3	G_2	C_3	G_3
pp	—	—	—	—	—	—	—	—	—	—	—	—
mf	12	12	12	10	8	10	10	10	12	8	10	12
ff	22	26	28	16	18	26	16	22	26	14	18	24

TABLE II

AVERAGE PERCENTAGES OF TOTAL ENERGY IN CONSTITUENT PARTIALS OF NINE TONES SUNG BY CT

	G_1			C_2			G_2		
Partial	pp	mf	ff	pp	mf	ff	pp	mf	ff
1	8.6	2.5	.9	7.4	4.0	2.1	16.3	14.1	2.1
2	13.0	4.6	1.3	20.3	8.3	4.5	77.0	59.2	6.5
3	7.5	5.1	2.4	28.6	25.3	8.2	6.0	16.9	56.1
4	31.7	8.7	4.8	30.7	58.3	11.9	.3	.7	6.5
5	31.9	45.2	3.4	2.3	1.4	62.8		5.9	22.1
6	5.5	30.8	27.9		.7	2.7			1.0
7	.6	.7	49.4		1.0				
8	.7	.4	.4	.4	.8	5.3			.3
9		.3	.2			1.2		.6	.3
10		.6	1.0						
11		.8	1.8						
12			6.0						
13									
14									.9
15									.4
16									.5
17									1.5
18									.4
19									.4
20									

TABLE III

AVERAGE PERCENTAGES OF TOTAL ENERGY IN THE CONSTITUENT PARTIALS OF NINE TONES SUNG BY AK

	G_2			C_3			G_3		
Partial	pp	mf	ff	pp	mf	ff	pp	mf	ff
1	28.3	7.1	4.3	56.6	18.1	7.3	71.2	39.4	3.1
2	30.7	14.2	8.0	40.1	26.7	16.1	13.4	31.1	31.8
3	36.8	56.4	32.0	2.6	37.9	57.3	14.2	22.9	36.1
4	2.6	9.7	18.3	.4	8.3	4.3	.3	4.6	1.1
5	.4	7.0	7.3		5.6	4.1	.2	.4	1.5
6	.5	3.4	20.2		1.8	1.9	.2	.3	.9
7	.3	.6							7.9
8		.3							2.8
9		.2			.6	1.0			5.2
10		.2			.3	5.9		.3	1.0
11						1.7			.7
12		.5	2.4			.2			.9
13			2.7						.1
14						.5			6.7

TABLE IV

AVERAGE PERCENTAGES OF TOTAL ENERGY IN CONSTITUENT PARTIALS OF NINE TONES SUNG BY OB

	C_2			G_2			C_3		
Partial	pp	mf	ff	pp	mf	ff	pp	mf	ff
1	37.3	6.4	5.5	42.5	10.1	1.3	61.5	18.6	1.0
2	6.5	3.8	3.0	21.2	7.1	2.5	35.1	63.0	37.3
3	5.2	3.8	2.2	26.7	63.6	70.1	3.2	11.8	3.1
4	23.2	57.3	36.1	3.4	3.4	3.6		4.4	52.9
5	19.9	14.7	17.0	.6	12.0	12.9		.7	
6	1.7	3.7	2.7	5.1	2.8	2.3			.5
7	.8	.6	1.7	.2	.3	.3			.3
8	3.0	8.3	25.5						.3
9	.3	.7	.5						.2
10								.9	1.1
11								.2	1.1
12									.4
13						1.2			
14						.3			.5
15						1.4			
16						2.2			
17						1.3			
18									.5
19									
20			.6						

TABLE V

AVERAGE PERCENTAGES OF TOTAL ENERGY IN CONSTITUENT PARTIALS OF NINE TONES SUNG BY HS

	G_2			C_3			G_3		
Partial	pp	mf	ff	pp	mf	ff	pp	mf	ff
1	22.7	6.1	3.2	17.6	3.0	1.6	17.4	4.6	.4
2	7.1	3.4	2.4	18.7	5.4	3.2	74.8	62.3	28.6
3	28.1	15.2	17.5	57.0	82.3	80.3	5.9	31.8	67.8
4	31.8	58.4	61.7	5.8	7.6	4.3	1.3	.4	2.0
5	5.7	8.6	8.5	.3	.7	2.0		.2	.2
6	3.7	6.6	5.4		.3	.2			.3
7	.2	.4	.5				.5	.6	.4
8	.5								
9									.2
10						.4			
11						1.5			
12						1.4			
13						2.8			
14				.3		1.2			
15		.6	.3			1.1			

BIBLIOGRAPHY

1. Bartholomew, W. T. Physical definition of "good voice-quality" in the male voice, *J. Acous. Soc. Amer.*, 6, 1934, 25.
2. Borchers, O. J. The nature and extent of the timbre vibrato in tones produced by trained vocalists. In press.
3. Fletcher, H. Loudness, pitch, and timbre of musical tones and their relation to the intensity, the frequency, and the over-tone structure, *J. Acous. Soc. Amer.*, 6, 1934, 59.
4. Ghosh, R. N. On the tone quality of the pianoforte, *J. Acous. Soc. Amer.*, 7, 1935, 27.
5. Hart, H. C., Fuller, M. W., and Lusby, W. S. A precision study of piano touch and tone, *J. Acous. Soc. Amer.*, 6, 1934, 80.
6. Laase, L. T. The effect of pitch and intensity on the quality of vowels in speech, *Arch. of Speech*, 1, 1937, 41.
7. Talley, C. H. A comparison of conversational and audience speech, *Arch. of Speech*, 2, 1937, 40.
8. Stevens, S. S. Relation of pitch to intensity, *J. Acous. Soc. Amer.*, 6, 1935, 150.
9. Miller, D. C. Science of musical sounds, N. Y., Macmillan, 1916.
10. Wolf, S. K., and Sette, W. J. Some applications of modern acoustic apparatus, *J. Acous. Soc. Amer.*, 7, 1935, 160.
11. Wolf, S. K., Stanley, D., and Sette, W. J. Quantitative studies on the singing voice, *J. Acous. Soc. Amer.*, 6, 1935, 255.

SUBSCRIPTION RATES

In order to materially increase the subscription list of the PSYCHOLOGICAL RECORD the editors announce the following subscription rates:

INDIVIDUAL SUBSCRIPTIONS

Vols. I and II	$1.00 each
Current subscription	$1.00 per year

INSTITUTION SUBSCRIPTION

Vols. I and II	$3.00 each
Current subscription	$4.00 per year

(Foreign subscriptions will be fifty cents (50c) additional to either of the above.)

Address orders to

THE PRINCIPIA PRESS, INC.

Bloomington, Ind.